# Cross-sections for Electron-impact Ionization of Tin ions from a Crossed-beams Experiment

**Stefan Schippers**

*Atom- und Molekülphysik*
*I. Physikalisches Institut*

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

www.uni-giessen.de/amp

# Outline

**electron-impact ionization of ions**

**Motivation**

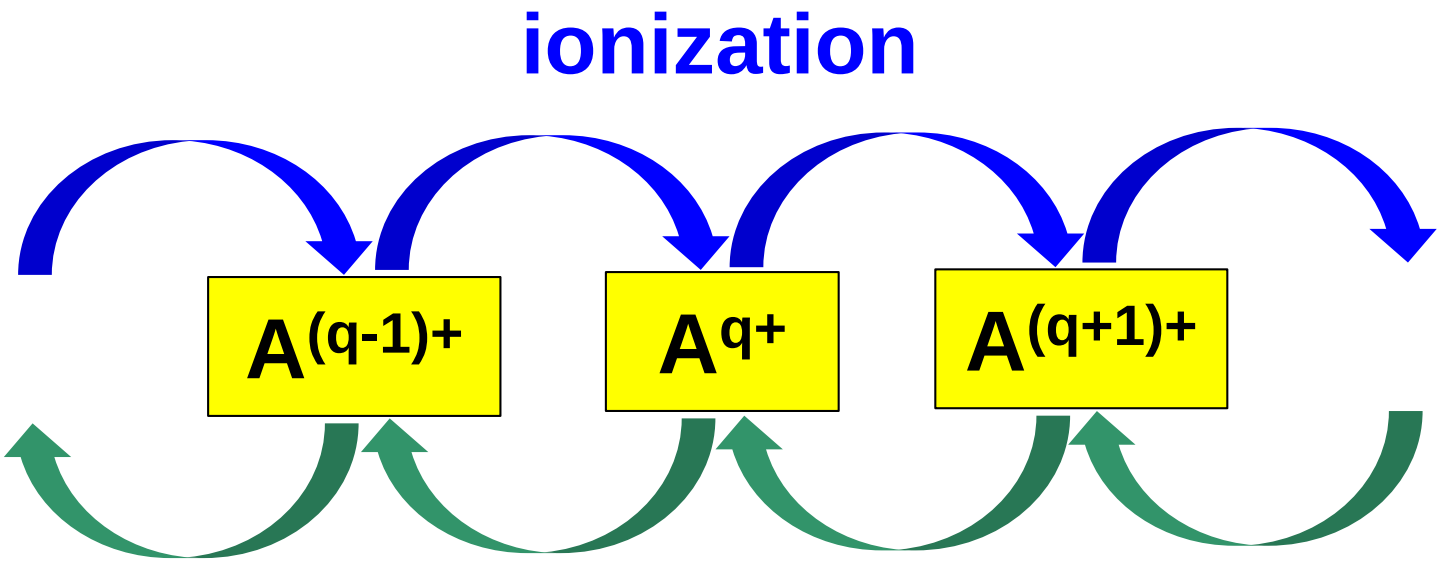
**Experimental technique**

**Results**

ionization rate coefficients for tin ions

**Outlook**

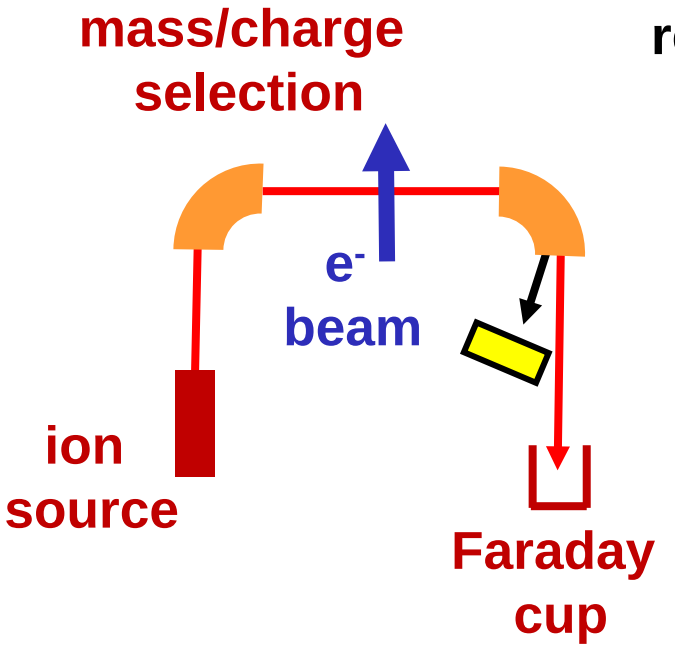
# Ionization Balance in a Plasma




We need to know **cross sections**
for
**electron-impact ionization**
and
**electron-ion recombination**

# Electron-Ion Crossed-Beams Method

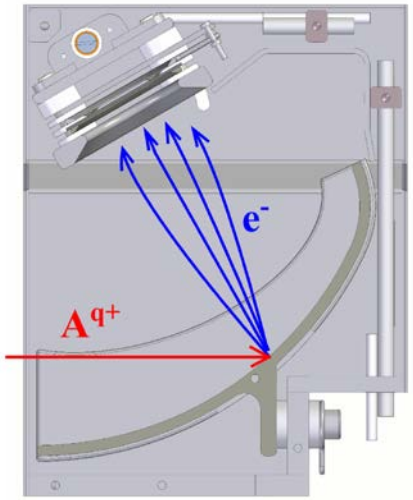
## charge-changing collisions




**reaction products**

- keV-beams of high directionality
- high particle energies in lab frame

**100% detection efficiency**



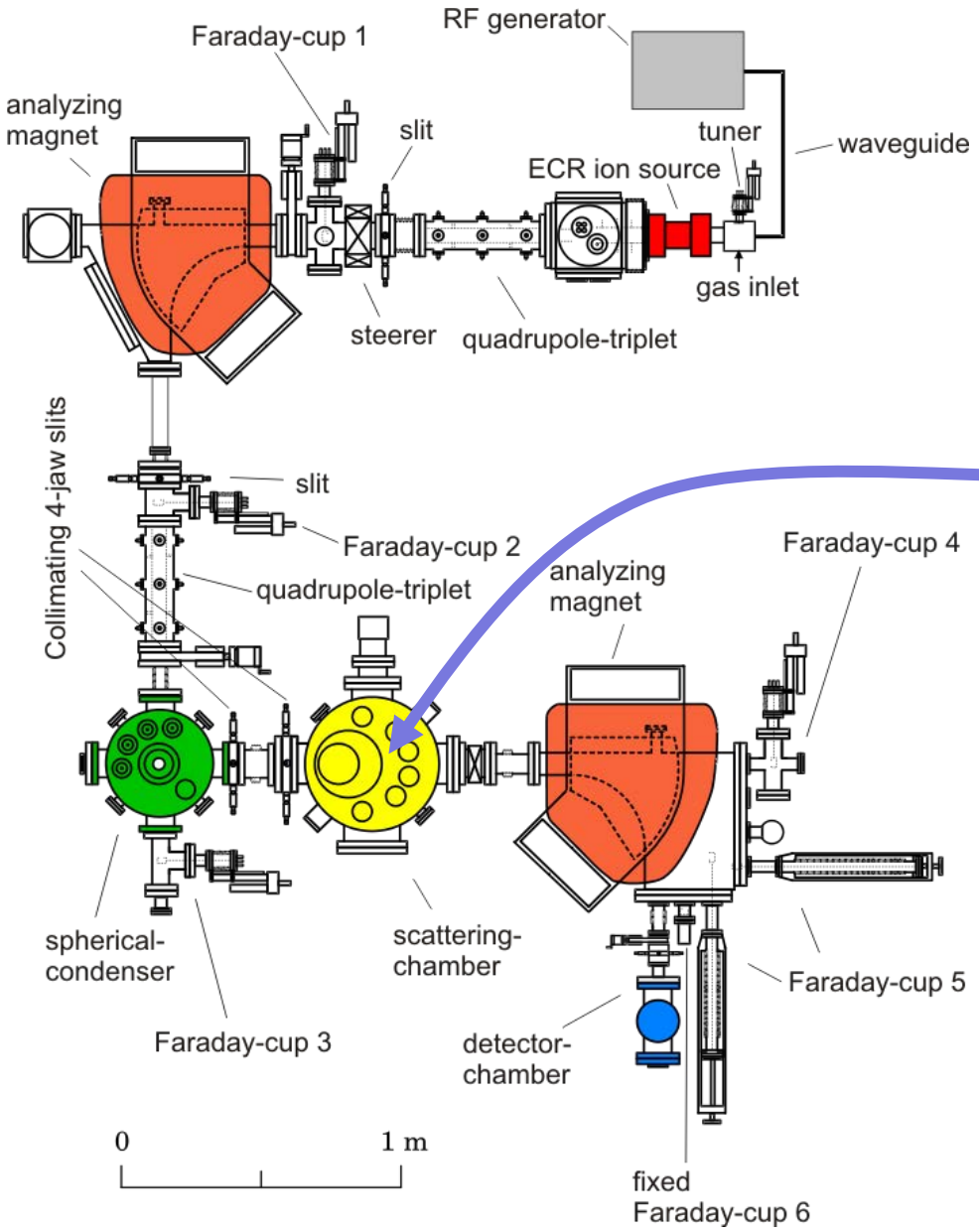

detector based on secondary electron emission

pioneered by Dolder et al.
Proc. R. Soc. A **264** (1961) 367

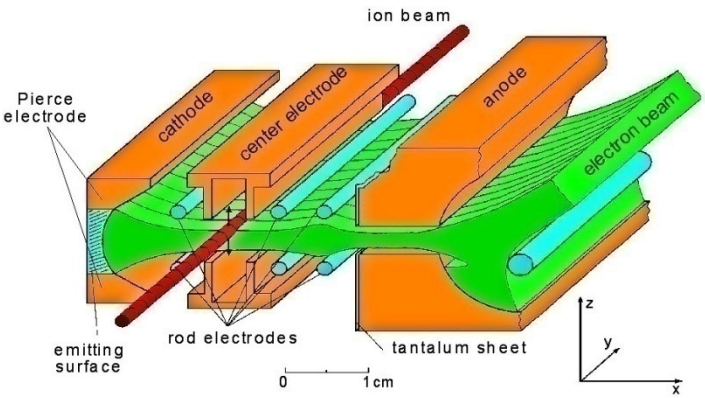
other groups: Giessen, Louvain-La-Neuve, ORNL

K. Spruck et al., RSI **86** (2015) 023303

# Giessen Crossed-Beams-Setup




## high-power electron gun

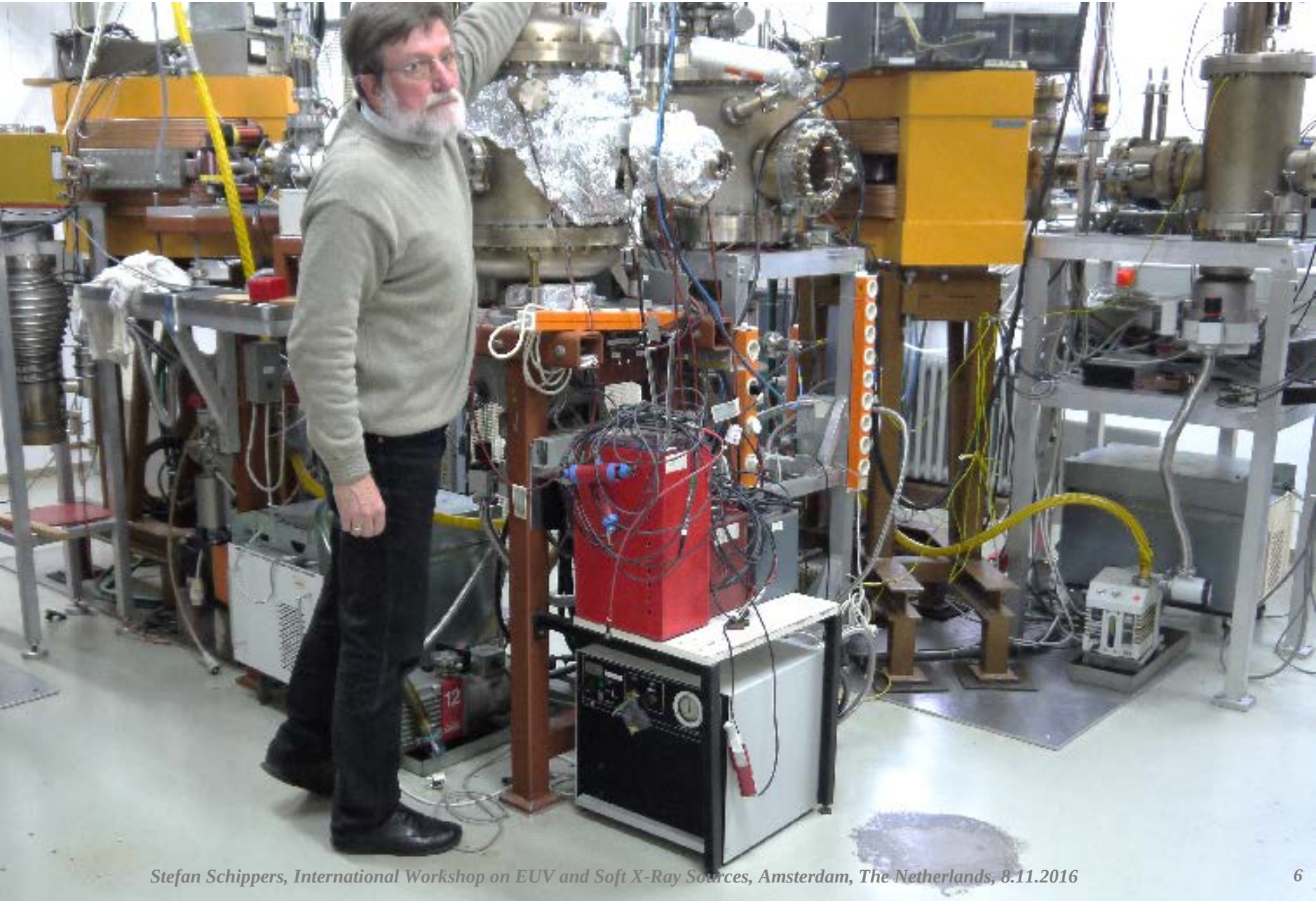



$E_{max}$ = 1 keV

$I_{max}$ = 460 mA

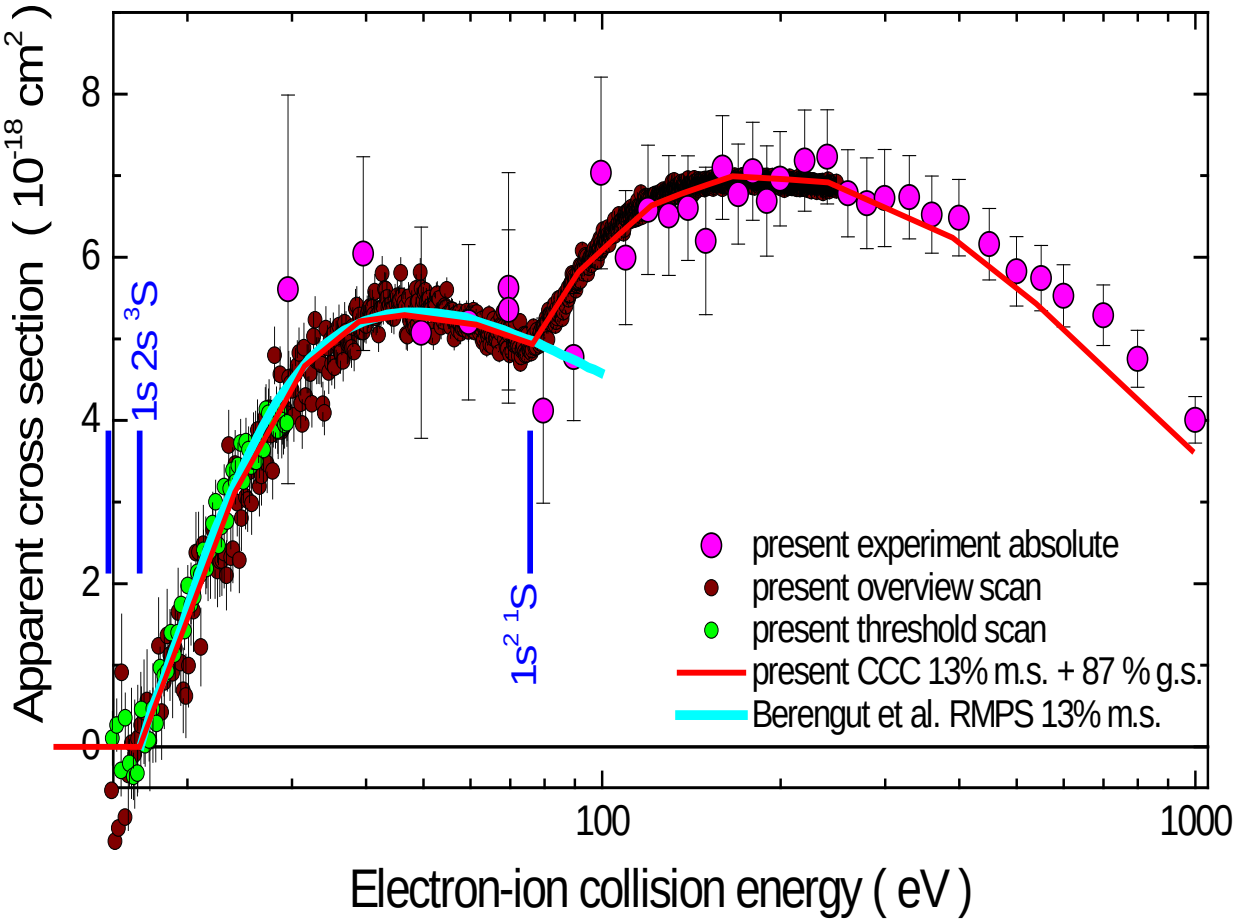
J. Jacobi et al., PRA **70** (2004) 042717

# Giessen Crossed-Beams Setup



# A Fundamental Collision System: $e^- + Li^+$

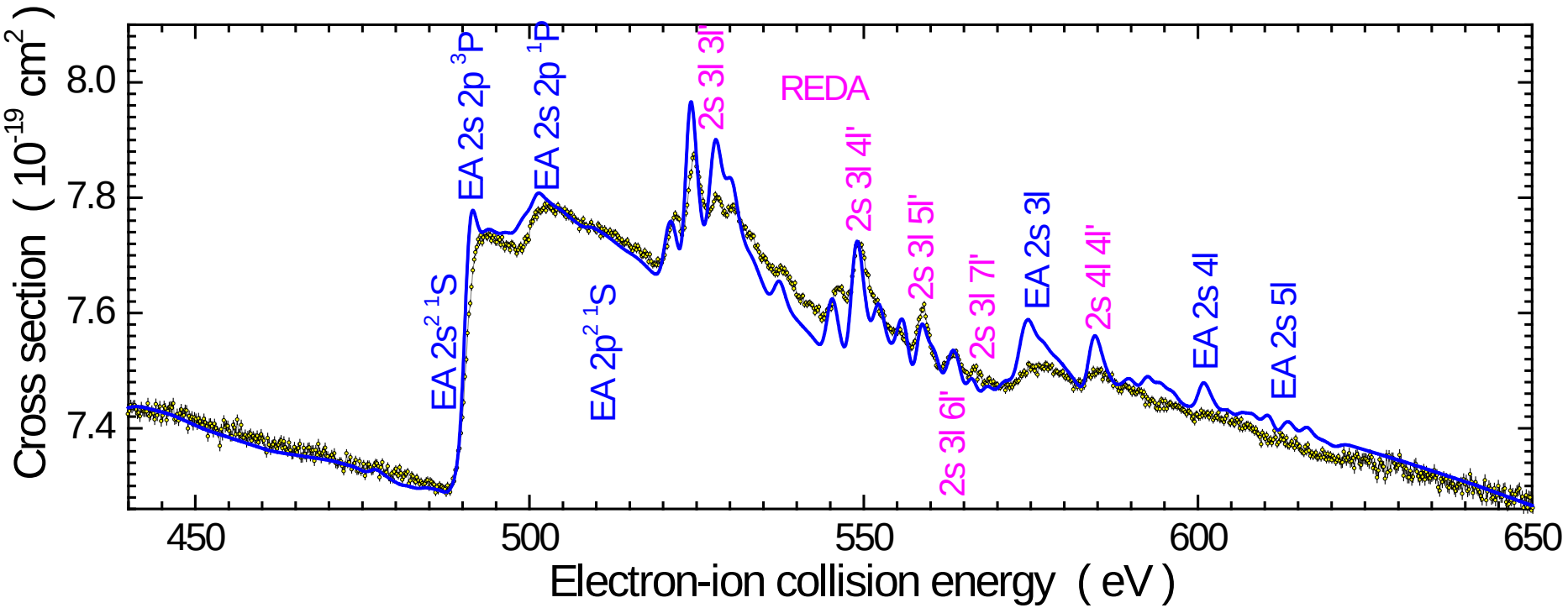
comparison between measurements and CCC calculations
for a mixture of $Li^+(1s^2\ ^1S)$ and $Li^+(1s\ 2s\ ^3S)$ ions




A. Borovik, Jr., A. Müller, S. Schippers, D. Fursa, I. Bray, JPB **42** (2009) 025203

# Higher-Order Ionization Processes

electron-impact ionization of metastable $N^{5+}(1s\ 2s\ ^3S)$
experiment and CCC calculations




EA: (nonresonant) Excitation followed by Autoionization

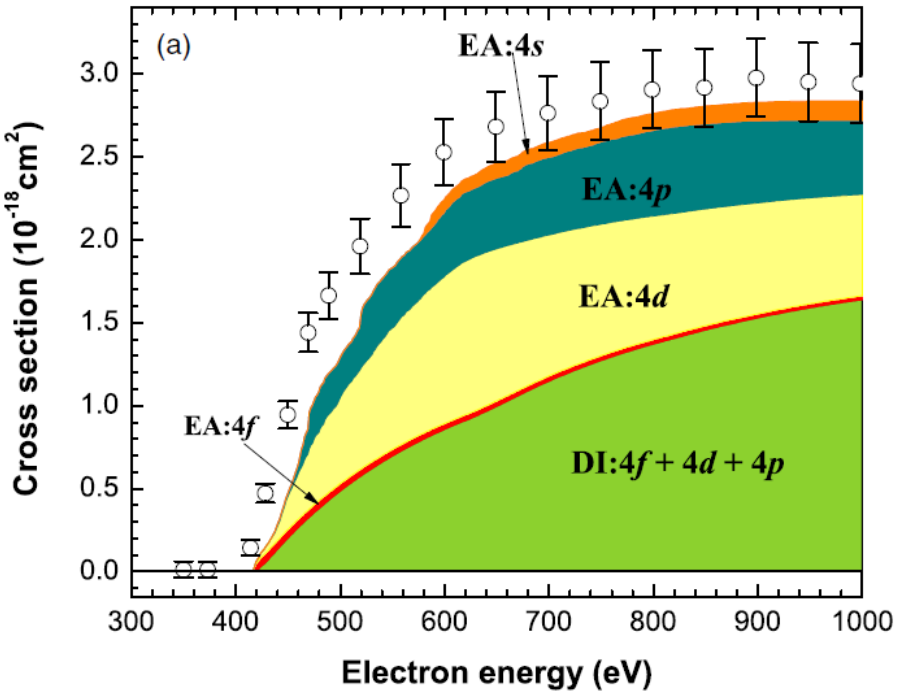
REDA: Resonant Excitation followed by Double Autoionization

A. Müller et al., PRA **90** (2014) 010701(R)

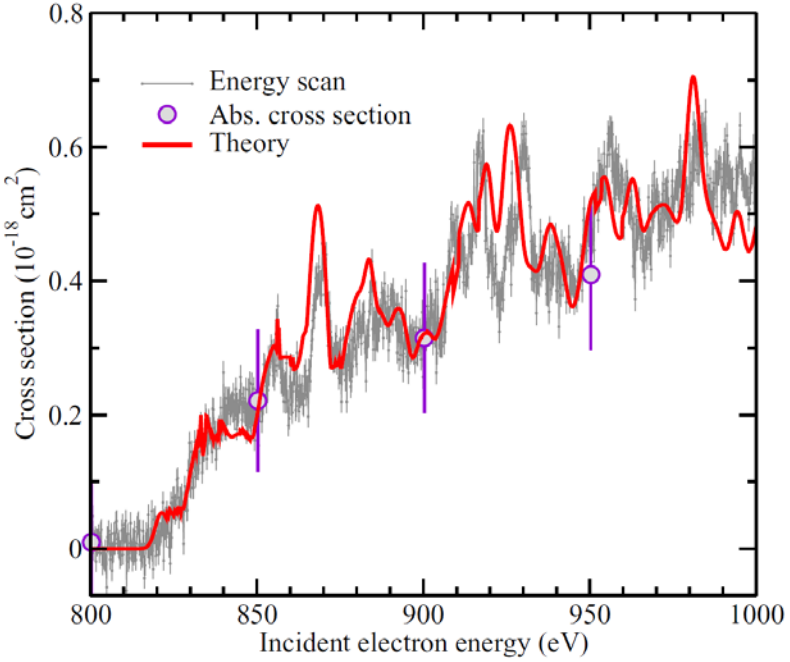
# Importance of Indirect Ionization

## excitations of up to at least n=25 have to be considered

single ionization of $W^{17+}$




single ionization of $Xe^{24+}$




D.-H. Zhang & D.-H. Kwon, JPB **47** (2014) 075202

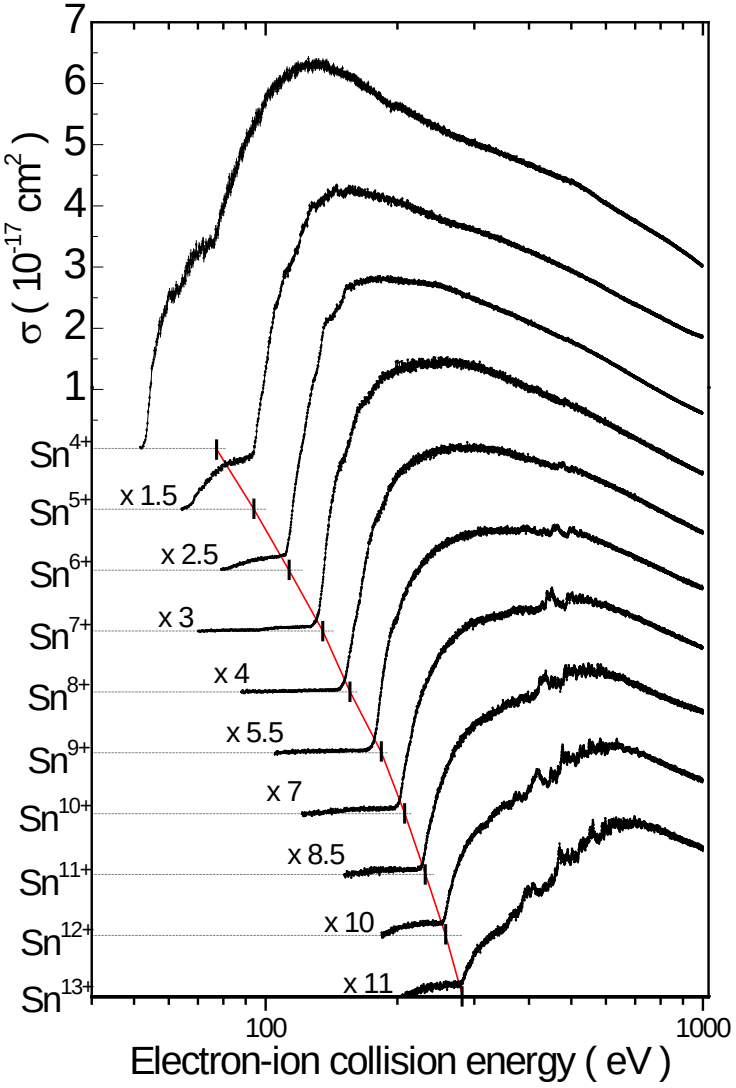
experimental data from Giessen

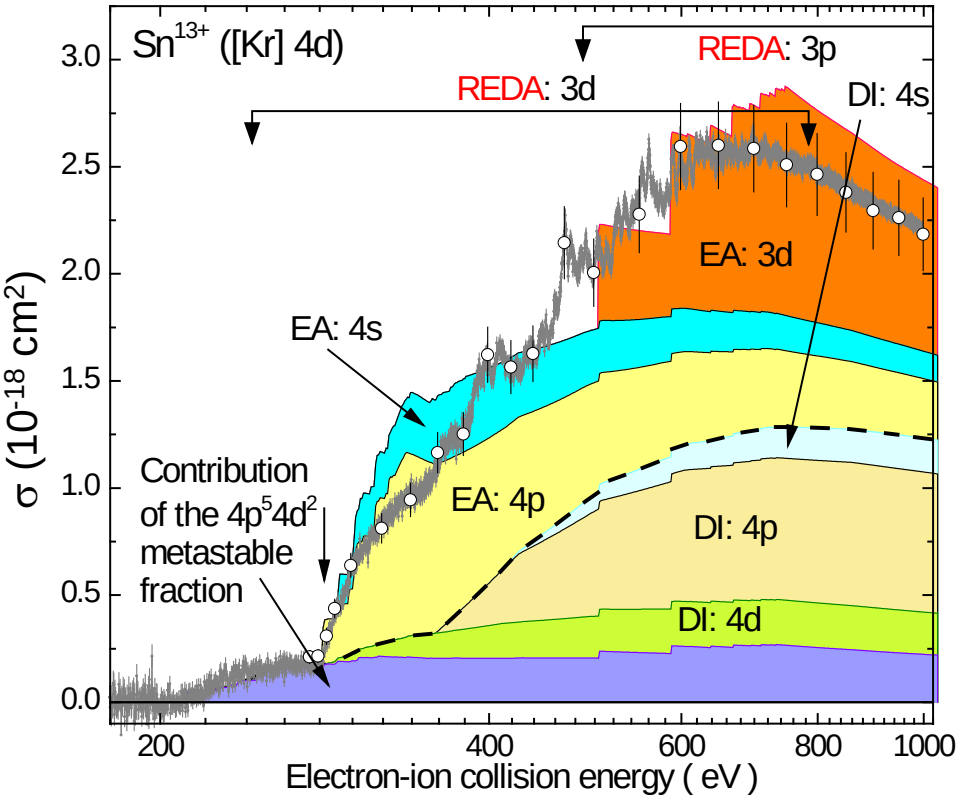
P. Liu et al., PRA **92** (2015) 012701

see, e.g., also: D.-H. Kwon & D. W. Savin, PRA **86** (2012) 022701;
V. Jonauskas et al., PRA **91** (2015) 012715;
A. Borovik Jr. et al., PRA **93** (2016) 012708.

# Cross-Section Data for Applications

## Ionization of $Sn^{4+}$ - $Sn^{13+}$ for EUV-Lithography

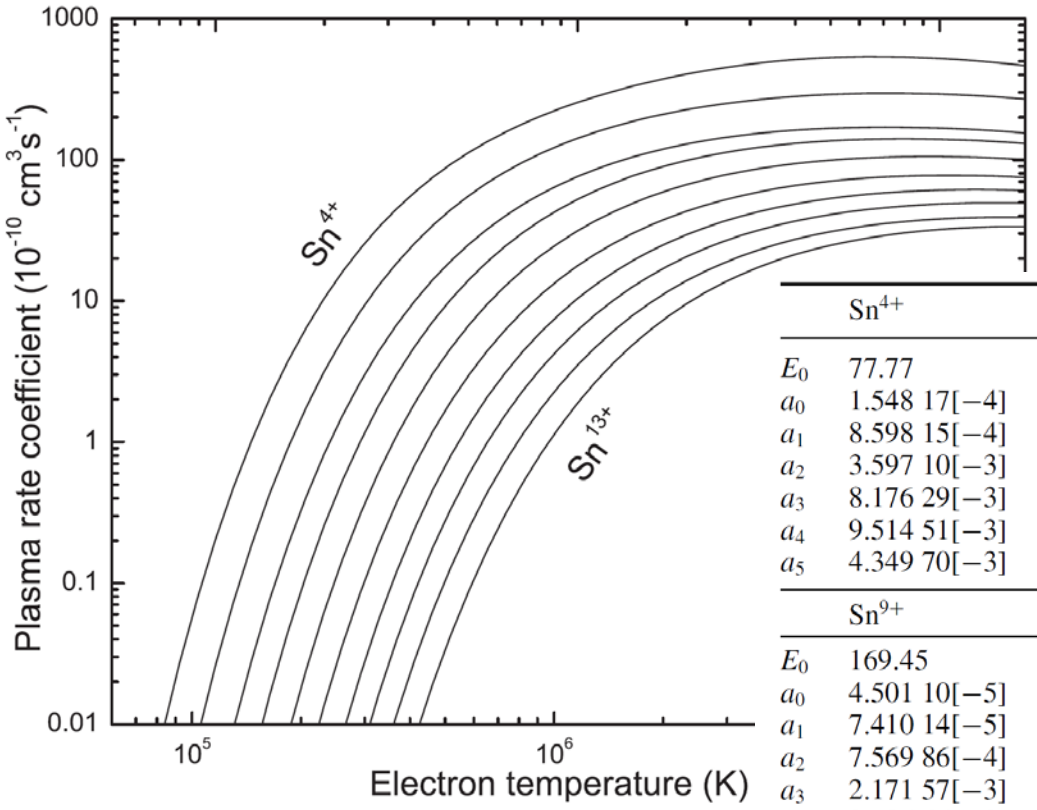



calculations using the LANL codes

Sn ions: A. Borovik, Jr. et al., JPB **46** (2013) 175201
Xe ions: A. Borovik, Jr. et al., JPB **48** (2015) 035203

# Rate Coefficients for EII of Sn Ions




$$\alpha(T) = \frac{4}{\sqrt{2\pi m_e}(k_b T)^{3/2}} \times \int_0^\infty \sigma(E) E e^{-E/k_B T}\, dE$$

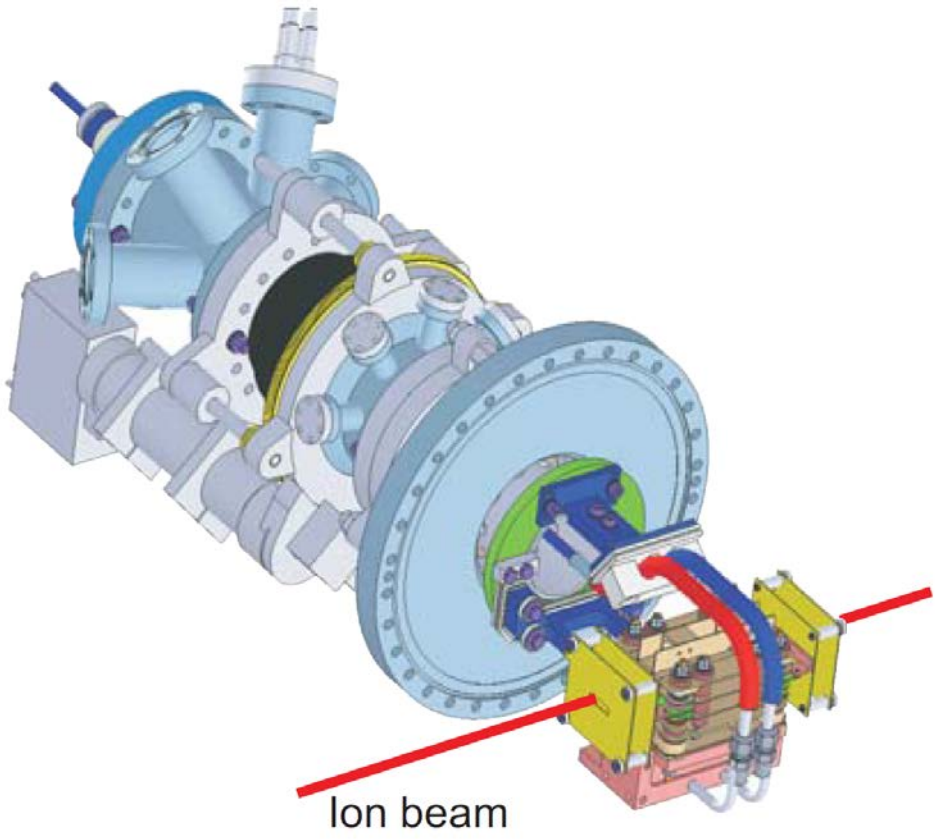
| | $Sn^{4+}$ | $Sn^{5+}$ | $Sn^{6+}$ | $Sn^{7+}$ | $Sn^{8+}$ |
|---|---|---|---|---|---|
| $E_0$ | 77.77 | 92.8 | 110.6 | 127.08 | 147.49 |
| $a_0$ | 1.548 17[−4] | 9.282 93[−5] | 8.059 03[−5] | 6.128 52[−5] | 5.168 48[−5] |
| $a_1$ | 8.598 15[−4] | 1.427 49[−4] | 1.390 86[−4] | 5.033 58[−5] | 1.023 45[−4] |
| $a_2$ | 3.597 10[−3] | 4.133 06[−5] | 1.457 75[−5] | 7.743 45[−4] | 9.988 80[−4] |
| $a_3$ | 8.176 29[−3] | 6.396 05[−4] | 5.161 30[−4] | 2.232 54[−3] | 2.801 83[−3] |
| $a_4$ | 9.514 51[−3] | 8.118 83[−4] | 8.124 88[−4] | 2.678 72[−3] | 3.399 21[−3] |
| $a_5$ | 4.349 70[−3] | 2.904 31[−4] | 3.673 00[−4] | 1.159 69[−3] | 1.509 63[−3] |
| | $Sn^{9+}$ | $Sn^{10+}$ | $Sn^{11+}$ | $Sn^{12+}$ | $Sn^{13+}$ |
| $E_0$ | 169.45 | 195.01 | 220.56 | 253.67 | 279.23 |
| $a_0$ | 4.501 10[−5] | 4.375 31[−5] | 4.108 34[−5] | 6.068 85[−5] | 3.378 61[−5] |
| $a_1$ | 7.410 14[−5] | 4.156 11[−5] | 1.638 75[−5] | 2.836 91[−4] | 9.190 77[−5] |
| $a_2$ | 7.569 86[−4] | 5.448 49[−4] | 3.174 27[−4] | 1.365 15[−3] | 7.212 84[−4] |
| $a_3$ | 2.171 57[−3] | 1.667 12[−3] | 1.029 00[−3] | 3.357 73[−3] | 2.146 57[−3] |
| $a_4$ | 2.685 45[−3] | 2.164 35[−3] | 1.408 43[−3] | 3.971 39[−3] | 2.763 38[−3] |
| $a_5$ | 1.210 10[−3] | 1.017 31[−3] | 6.927 23[−4] | 1.819 71[−3] | 1.328 07[−3] |

*Parameterization with only 7 parameters*

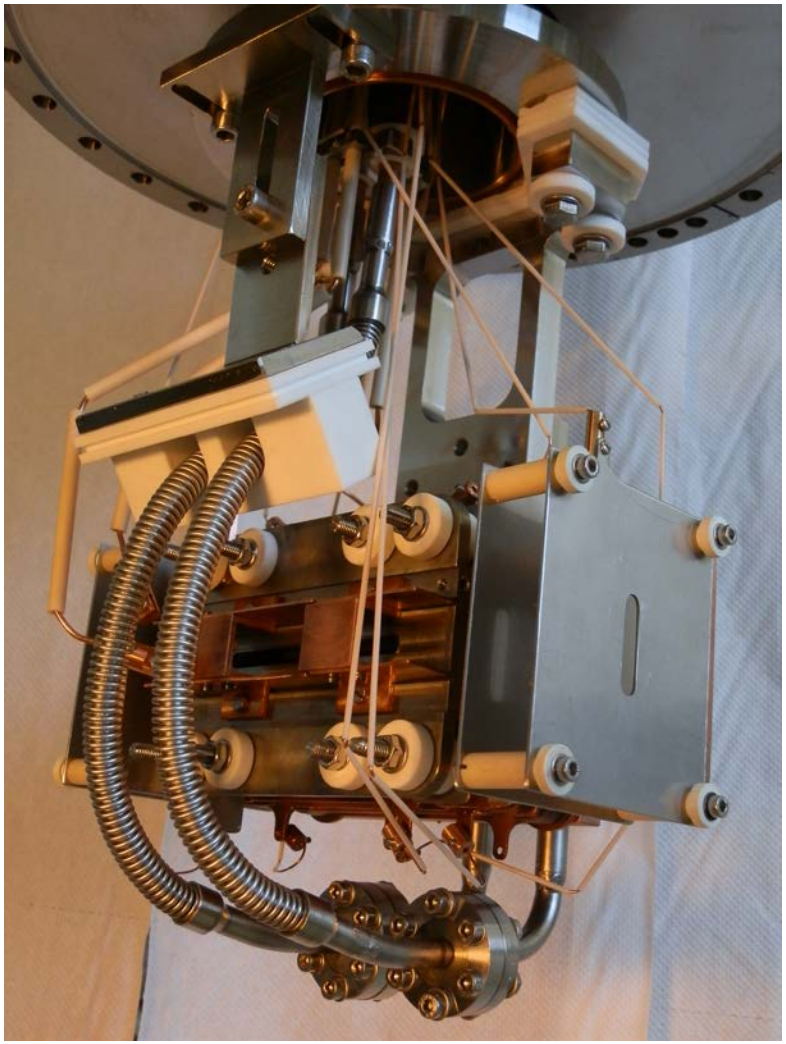
$$\alpha(T) = \frac{\rho(x) E_1(1/t)}{\sqrt{t E_0^3}} \qquad x = 1 - \frac{\ln 2}{\ln(t+2)} \qquad t = k_B T / E_0 \qquad \rho(x) = \sum_{i=0}^{5} a_i x^i$$

A. Borovik, Jr. et al., JPB **46** (2013) 175201

# New High-Energy High-Density Electron Gun

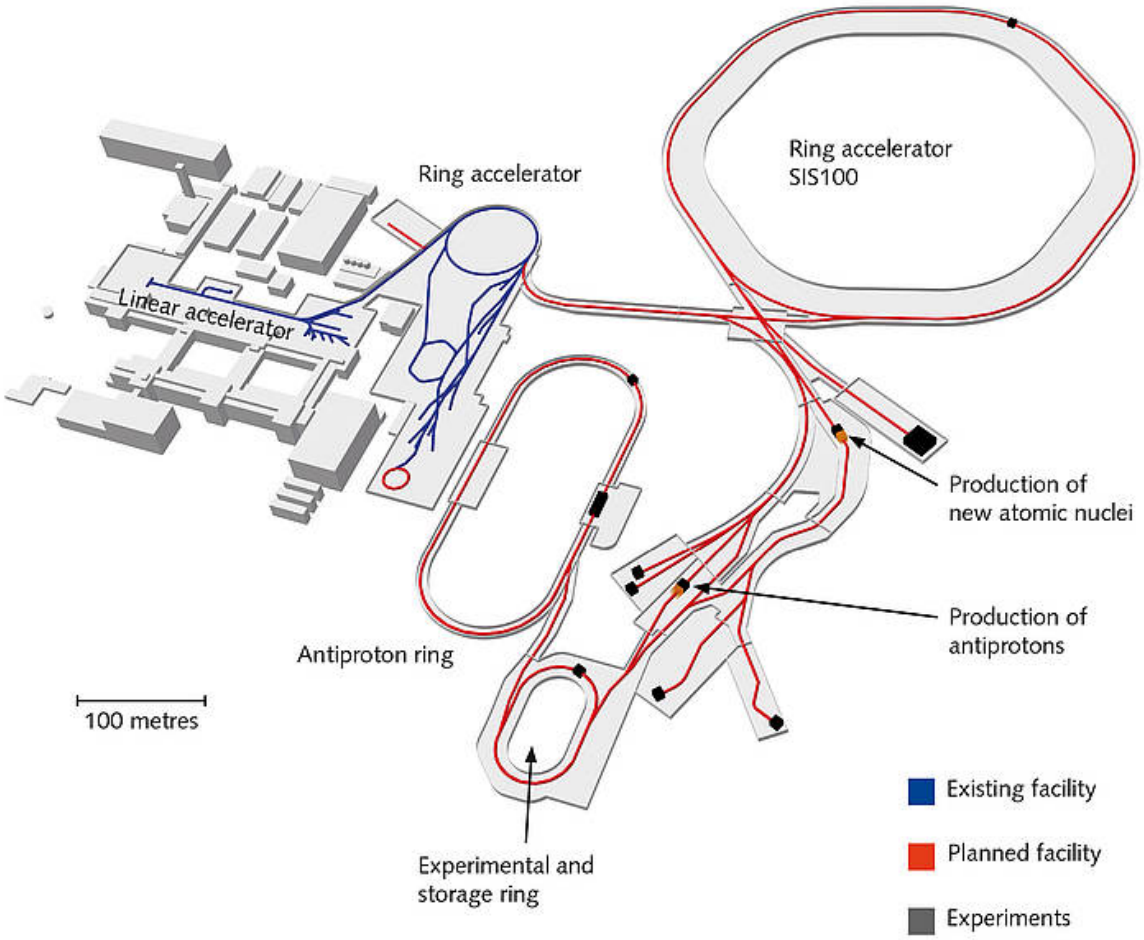


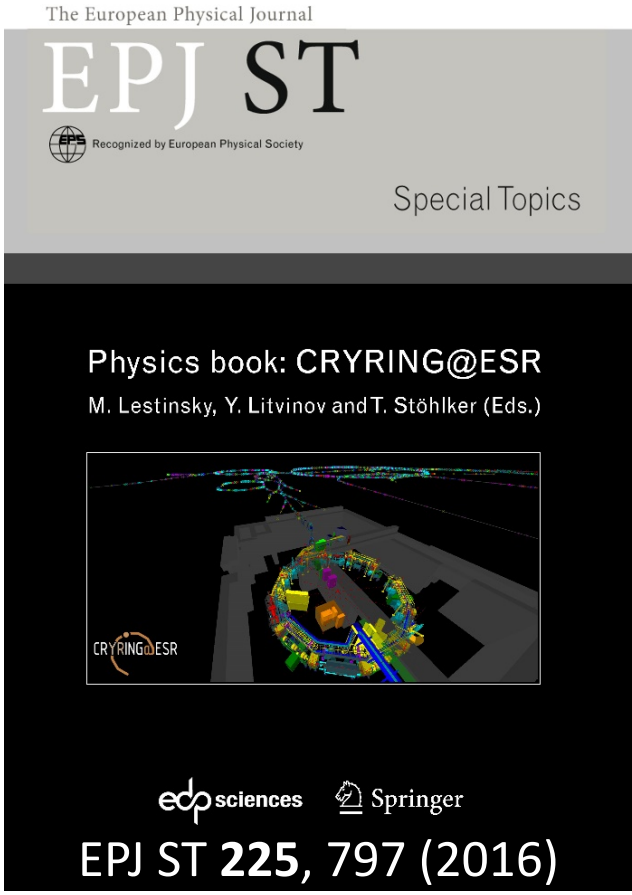

3500 eV, 1 A



A. Borovik, Jr. et al., JPCS **488** (2014) 142007

# Future Electron-Ion Collision Experiments at the FAIR Facility in Darmstadt




www.appa-rd.fair-center.eu

# Collaborators

**Alexander Borovik Jr.**

Benjamin Ebinger

Mohammad Gharaibeh*

Pierre-Michel Hillenbrand**

Tobias Molkentin

Alfred Müller

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

www.uni-giessen.de/amp

Stefan Schippers

* now at Qatar University, Doha, Qatar
** now at Columbia Astrophysics Laboratory, New York, USA

# Summary

crossed-beams experiments with free electrons

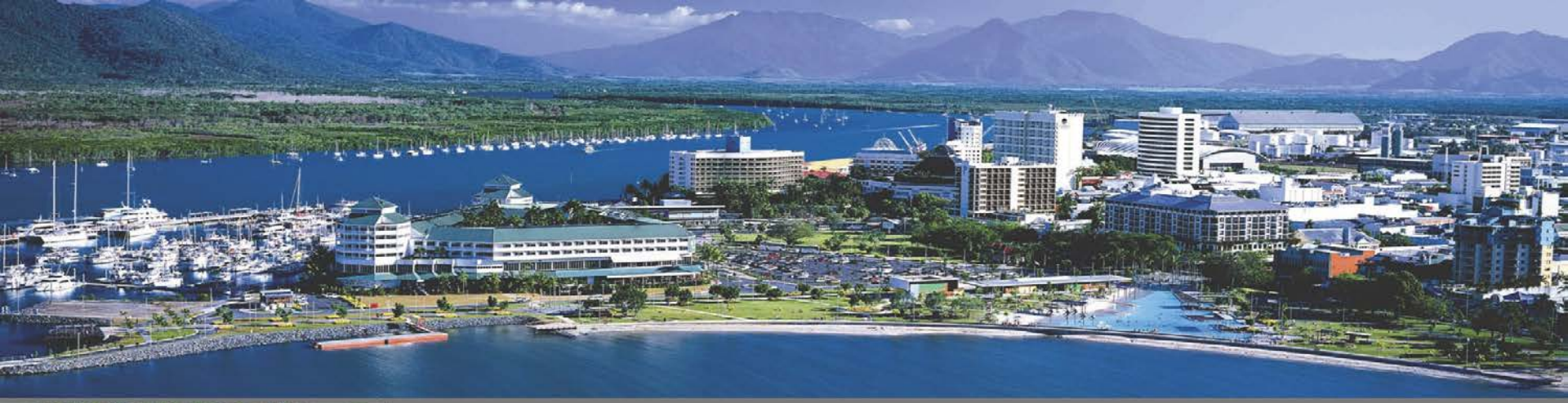
electron-impact ionization

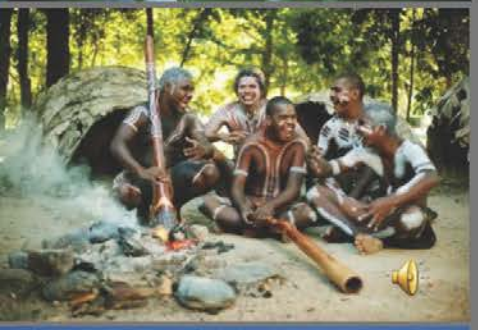
**absolute cross sections**
for applications in plasma physics and astrophysics

importance of indirect and higher-order ionization processes

consistent set of ionization rate-coefficients for tin ions

new experimental developments





# International Conference on Photonic, Electronic and Atomic Collisions (XXX ICPEAC)

## July 26 to August 1, 2017, Cairns Tropical Queensland, Australia

## http://icpeac30.edu.au/